A.5.1.2.6 Verification Tests for Consistency of Performance in Design Qualification.

Design qualification testing is only meaningful if the tested unit(s) is representative of expected design performance. Vessels submitted for design qualification are expected to have representative initial burst pressure and pressure cycle life. The following tests are designed to verify consistency of performance within the batch of vessels used to qualify the design.

A.5.1.2.6.i. Burst Pressure.

The manufacturer will supply documentation (measurements and statistical analyses) to establish that the burst pressure of every unit is controlled to > 180% NWP. In addition, the manufacturer will supply documentation to establish the midpoint burst pressure of new storage containers, BP_0, and to establish that the burst pressure of every unit is controlled to > 90% BP_0. [To accommodate at least $\pm$10% manufacturing variability, BP_0 must be $\geq$ 200% NWP.]

Three (3) new vessels randomly selected from the design qualification batch of at least 10 vessels are hydraulically pressurized until burst (6.4.2.1 test procedure). All vessels tested must have burst pressures $\geq$ 180% NWP and within $\pm$10% of BP_0.

A.5.1.2.6.i(a) Rationale for A.5.1.2.6.i: Verification Tests for Consistence of Performance in Design Qualification -- Burst Pressure.

This test is designed to verify the baseline initial burst pressure, BP_0, for use in design qualification (B.5.1.2.8), to verify that the variability of initial burst pressure of production units is less than $\pm$ 10% of BP_0 (B.5.1.1.1), and to establish the reference point for production quality control (A.5.1.2.7.ii(a)) where it is used to provide assurance that produced vessels correspond to the vessels used to qualify for on-road service.

Rationale: Design qualification provides assurance of on-road performance only if systems tested in design qualification are representative of all produced storage systems. Safety risk results if a system tested in design qualification is considerably stronger or more durable or more reliable than the typical system. Therefore, design qualification provides testing to verify that variability in burst pressure is within the $\pm$ 10% range accommodated by qualification testing. The manufacturer cannot present systems for testing that have superior properties to subsequent production units, and cannot report an unrepresentatively low value for BP_0 to allow for future production of weaker units.

A.5.1.2.6.ii. Pressure Cycle Life

The manufacturer will supply documentation (measurements and statistical analyses) to establish that the pressure cycle life (PCL) if every production unit is $\geq$ 5500. In addition, the manufacturer will supply documentation to establish the midpoint pressure cycle life of new storage containers, PCL_0, or the manufacturer may simply stipulate that PCL_0 is $\geq$ 11,000 cycles (2 times the minimum number of cycles required for all production units).

Three (3) new vessels randomly selected from the design qualification batch of at least 10 vessels will be hydraulically pressure cycled to 125% NWP for 11,000 cycles (2 times the number of cycles required in 5.1.2) or until leak occurs (B.6.2.2.2 test procedure). The pressure cycle life, PCL, is the number of cycles until leak. All vessels tested must have PCL $\geq$ 5500. If no leak occurs within 11,000 cycles, then the pressure cycle life, PCL, is equated to 11,000.

If the PCL of each vessel is not within $\pm$ 25% of PCL_0, then three (3) vessels will be required to undergo the testing in B.5.1.2, the Durability (Hydraulic) Performance Test. If the PCL of each vessel is within $\pm$ 25% of PCL_0, then one (1) vessel will be required to undergo testing according to B.5.1.2.

Leak Before Burst: Each of the vessels that have not leaked during the cycling to establish PCL will continue to cycle without rupture for an additional 11000 cycles (for a total of 22000 cycles, 4 times the number of cycles required in 5.1.2) to establish residual resistance to fatigue rupture.

A.5.1.2.6.ii(a) Rationale for A.5.1.3.6.ii: Verification Tests for Consistency of Performance in Design Qualification – Pressure Cycle Life.

This test is designed to provide assurance that vessels qualified for on-road service are representative of production vessels. Design qualification provides assurance of on-road performance only if systems tested in design qualification are representative of all produced storage systems. Safety risk results if a system tested in design qualification is considerably stronger or more durable or more reliable than the typical system.

The design qualification provides testing to verify that if the mid-point of pressure cycle life measurements is close to the minimum performance requirement (i.e., between 5500 and 11000), then the variability in pressure cycle life should not be so large (> ± 25%) as to leave doubt that a much superior system may be qualified but routine production systems with much lower fatigue resistance may not have reserves sufficient to satisfy the full series of testing even though they may satisfy the 5500 ambient-temperature pressure cycle life minimum. Therefore, if the pressure cycle life of vessels is close to the minimum requirements (between 5500 and 11000) and the variability is high (> ± 25%), then 3 vessels must be tested testing in B.5.1.2, the Durability (Hydraulic) Performance Test, to establish that vessels distributed within the wide range of production meet durability test requirements. If the pressure cycle life of vessels is well above the minimum requirement (> a factor of 2) or if the variability of pressure cycle life in production vessels is not large (< 25%), then a single randomly selected vessel will sufficiently represent production for verification of durability test requirements.

Leak-Before-Burst is established as the probable sequence of failure to provide secondary mitigation against burst. (Note: the primary mitigation is provided by design qualification according to B.5.1.2 and B.5.1.3). The detection of leak results in vehicle shut-down, which is expected to result in the repair or replacement of the vessel before a burst condition develops. For systems with extraordinary resistance to leak and rupture (i.e., no leak within 22000 full fill cycles, expected to be equivalent to over 10 million km (6 million mi) of driving, the order of the failure occurrence is too far (greater than 6x) beyond real-world conditions to be meaningful. Leak-before-burst is demonstrated under the most stressful repeatable on-road conditions which are < 2MPa to 125% NWP pressure cycles. (Note: testing with high cycle counts to higher pressures would provide for faster testing, but could elicit failure modes that could not occur in real world service.)

A.5.1.2.7 Verification Tests for Conformity of Production with Design Qualification

Design qualification testing is only meaningful if the tested unit(s) is representative of expected performance of production units. Manufacturers are expected to ensure that all production units meet the requirements of performance verification testing in B.5.1.2. Establishing of key metrics of units tested for performance is required for documentation of correspondence of manufacturing units.

Manufacturers of storage systems must provide the following information to regulatory authorities upon request.

A.5.1.2.7.i Documentation of Routine Production (Each Produced Unit). Documentation should include the following production controls.

a. Routine leak test in 4.3 should be conducted at NWP

b. Routine proof pressure test should be conducted on the containment vessel to 150% NWP (Appendix C.1). Routine proof pressure tests on all piping and closures (such as shut-off valve(s), Dimension checks during the proof pressure test should establish that the production is statistically consistent with the characteristics of the units used in performance verification (design qualification) testing.

c. NDE examination to verify that vessel flaw sizes are below the design specifications. The NDE method shall be capable of detecting the maximum defect size allowed.

d. Appropriate tests for manufacturing quality control. For example,

1. For metallic containment vessels and liners, hardness tests (ISO 6506-1 or equivalent tests) after final heat treatment to verify hardness is in the design range.

2. Examination of welded liners, in accordance with 6.8.2 of EN 13322-2:2003 for stainless steel liners and 6.2.3 of EN 12862:2000 for aluminum alloy liners
3. Verification of the design specified surface finish including folds in the neck or shoulder of forged or spun end enclosures and openings

e. Components providing closure functions, such as the containment vessel shut-off valve, check valve, and the TPRD and vent line must have been tested and qualified for vehicle service in accordance with CSA standards (or ISO or other ANSI-certified standards) for use in onboard compressed hydrogen storage applications.

A.5.1.2.7.ii. Documentation of Periodic Production Tests (Batch/Lot Tests). Periodic (batch) testing should be designed according to the manufacturer's documented quality control protocol established in A.1.5.2.6. Documentation of periodic (batch) testing should include statistical analyses supported by the following required measurement requirements.

At least one vessel must undergo (a) burst pressure testing and (b) pressure cycle testing per production batch. The same vessel may be used for both the pressure cycle and burst tests. If a vessel fails to meet the burst pressure requirement or the pressure cycle requirement, then all production since the previous successful periodic/batch test shall be rejected (not qualified for use in vehicle service).

(a) Burst pressure test to confirm the burst pressure is $\geq$ 180% NWP and $\geq$ 90% BP_0 (BP_0 is established in B.5.1.1.1 and discussed in A.5.1.2.6). [The requirement that the burst pressure of production units be controlled to > 90% BP_0 and $\geq$ 180% NWP provides assurance that the full range of production vessels are accommodated in performance requirements and effectively requires that $BP_0 \geq$ 200% NWP.]

Appropriate multi-batch statistics shall be used to monitor trends in the overall production midpoint, and appropriate corrective action will be undertaken as needed to maintain the midpoint burst pressure of units at $\geq BP_0$.

A.5.1.2.7.ii(a)(1) Rationale for A.5.1.2.7.ii(a) is contained within A.5.1.2.6.i(a)

(b) Pressure cycle test to confirm absence of leak and rupture within 5500 cycles. Subsequently, on the same vessel, conduct proof pressure test to 180% NWP for at least 30 seconds to establish additional resistance to rupture under static stress

Appropriate statistics of batch pressure cycle life measurements shall be used to verify the multi-batch production midpoint is maintained at $\geq PCL_0$

A.5.1.2.7.ii(b)(1) Rationale for A.5.1.2.7.ii(b) is contained within A.5.1.2.6.ii(a):

PART B

B.5.1.1 Verification Tests for Baseline Metrics

B.5.1.1.1 Baseline Initial Burst Pressure.

The manufacturer shall supply documentation (measurements and statistical analyses) that establishes the median burst pressure of new storage containers, BPo. The BPo is used to satisfy requirements of B.5.1.2.8 and B.5.1.3.5 for design qualification (performance verification).

Three (3) randomly selected new vessels from the design qualification batch of at least 10 vessels will be hydraulically pressurized until burst (6.4.2.1 test procedure). All vessels tested must have burst pressures $\geq$ 180% NWP and within $\pm$10% of BP_0.

B.5.1.1.2 Baseline Initial Pressure Cycle Life

The manufacturer will supply documentation (measurements and statistical analyses) to establish that the pressure cycle life (PCL) if every production unit is $\geq$ 5500. In addition, the manufacturer will supply documentation to establish the midpoint pressure cycle life of new storage containers, PCL_0, or the manufacturer may simply stipulate that PCL_0 is $\geq$ 11,000 cycles (2 times the minimum number of cycles required for all production units).

Three (3) new vessels randomly selected from the design qualification batch of at least 10 vessels will be hydraulically pressure cycled to 125% NWP for 11,000 cycles (2 times the number of cycles required in 5.1.2) or until leak occurs (B.6.2.2.2 test procedure). The pressure cycle life, PCL, is the number of cycles until leak. All vessels tested must have PCL $\geq$ 5500. If no leak occurs within 11,000 cycles, then the pressure cycle life, PCL, is equated to 11,000.

If the PCL of each vessel is not within $\pm$ 25% of PCL_0, then three (3) vessels will be required to undergo the testing in B.5.1.2, the Durability (Hydraulic) Performance Test. If the PCL of each vessel is within $\pm$ 25% of PCL_0, then one (1) vessel will be required to undergo testing according to B.5.1.2.

Leak Before Burst: Each of the vessels that have not leaked during the cycling to establish PCL will continue to cycle without rupture for an additional 11000 cycles (for a total of 22000 cycles, 4 times the number of cycles required in 5.1.2) to establish residual resistance to fatigue rupture.